REAL TIME HOLOGAPHIC
INTERFEROMETRY

James Wilford Somers

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THESIS

REAL TIME HOLOGRAPHIC
INTERFEROMETRY

by

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This thesis presents an introduction into holographic interferometry with its history and applications. Problems involved with recording, developing, and reconstructing real time holographic interferograms are presented. Reconstruction was accomplished using both a conventional camera and a movie camera. A flexible experimental arrangement was used which was applied to the problem of analyzing heat flow in a square enclosure. This problem was examined and some introductory information is presented.

Real Time Holographic

Interferometry

by

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ABSTRACT

This thesis presents an introduction into holographic interferometry with its history and applications. Problems involved with recording, developing, and reconstructing real time holographic interferograms are presented. Reconstruction was accomplished using both a conventional camera and a movie camera. A flexible experimental arrangement was used which was applied to the problem of analyzing heat flow in a square enclosure. This problem was examined and some introductory information is presented.

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I. INTRODUCTION

Holography is the recording and reproduction of both the amplitude and phase information of the light emanating from a source. Thomas Young in 1802 used a single double-aperture experiment to demonstrate that light propagates as a wave and forms interference patterns. Wiener in 1890 set up a standing wave experiment and demonstrated that the interference pattern recorded on a photographic plate was caused by the electric field, with the magnetic field having no effect. Prior to holography, attempts were made to record both the phase and intensity data using stereo methods. Two photographs were taken of the same object from two different angles and encoded to enable the viewer to see one with the right eye and the other with the left. The eye tends to blend these two into a three-dimensional image, but accurate phase information is only possible if viewed from the camera's original position. Leppmann introduced integral photography to produce correct phase and intensity information from many positions using photographs taken from many "points of view." This image appeared as if obscured by a screen.

Dennis Gabor, considered the father of holography, used holography to obtain accurate phase and intensity information without the obscured screen or limited point of view effects. He made advances in holographic applications to electron optics in 1948 and 1949, although this and other early works were hampered by the lack of an intense coherent light source. With the invention of the laser, holography has

advanced exponentially. Leith and Upatnieks deserve credit for much of the laser holography done in the early 1960's.

Advances in holography using the laser have created many practical uses. Works at The NASA Marshall Space Center have shown that three-dimensional movies can be made using a real-time three-dimensional motion picture camera. An argon laser of 5145Å and 70mm film were used. A reflection hologram arrangement was used with the object slowly moving. Instead of recording on hologram plates, film was used at the rate of 10 frames per second. After processing and reilluminating, the movement can be observed. Hologram flying-spot storage has shown the practicality of optical storage in a computer memory cell. Erasable and reusable photo-conductor-photoplastic film enhances computer storage using holography. RCA Corp's Aerospace Systems Division has demonstrated the basic feasibility of storing two-dimensional maps on cassettes. These will provide aircraft crews with three-color displays of their location and route. Holography was considered because it gives improved resolution and physical characteristics over conventional film. Double exposure, real-time, and dual-hologram interferometry have industrial applications. AFSC's Aerospace Research Laboratories have shown dual-hologram interferometry using a dual-hologram holder to be very useful in wind-tunnel testing. Boundary layer studies are an off-shoot of this technique. Double-exposure interferometry is now required of industry by some government contracts in order to pinpoint defects. Real-time interferometry and some of its applications will be described in this paper. These examples of current holographic technology show the potential for applications which will solve practical problems.

II. NATURE OF THE PROBLEM

Heat flow in a square box is difficult to analyze empirically. Using standard techniques, sensors can be located in and around the box to record temperature changes and flow rates. Initial, steady-state, and some transient phenomenon can be recorded. Sensors used for gathering data will inherently change the temperature and flow pattern. Holographic technology allows the analysis of the changing density fields inside the box without the need for sensors. Real-time holographic interferometry allows a continuous flow of information and a representation of the effects of non-symmetrical heat addition. This is shown in the heating of the bottom of a square box filled with distilled water. These techniques can also be used in other fluids and solids to produce realistic experimental setups for many testing requirements.

Holographic interferometry has many advantages over classical interferometry. Classical methods could not be used on three-dimensional objects due to the complexity of data reduction. Also classical interferometry was impossible through imperfect or diffusing objects. High quality and expensive equipment with fine alignment was another requirement. Holography eliminated some of these problems by dividing a single coherent light source into an object and a reference beam. The quality of interferometry using double exposure holography no longer depended on high precision optics or test sections. For the purpose of this paper interferometry will be used in the holographic sense.

Three common types of holographic interferometry are single exposure, double exposure, and dual single exposure. All three methods are important and present distinct advantages and disadvantages.

Single exposure holography consists of recording the amplitude and phase information from an object on a hologram plate by using an object and a reference beam which originate from the same source (Figure 1). The plate is processed and replaced in the exact position in which it was recorded. When the plate is reilluminated by the reference beam the observer looking through the plate sees a virtual image of the original object at its original location (Figure 2). By reversing the reference beam or the plate, a real image of the object will be projected (Figure 3). Live fringe single exposure holography involves making a hologram of an object and superimposing the reconstructed virtual image on the still-illuminated object. If the original object is changed at all by the effect of temperature, pressure, strain, or motion, an exact superposition will create a cancellation or reinforcement of the wave intensities and a fringe pattern will be established. Bright fringes are located wherever the difference between the perturbed and the reconstructed wavefront is equal to $2\pi M$ where M is a real whole number. Problems arise in achieving exact replacement of the original hologram and in shrinkage of the emulsion which displaces the virtual image. If there is substantial relative motion between parts of the apparatus during replacement of the hologram the fringes are lost.

Double-exposure interferometry involves exposing the hologram plate twice with the same object under two different conditions. This produces a locked-in fringe pattern in which each exposure is affected

equally by emulsion shrinkage or illumination differences. The re-alignment problem is eliminated, but only one perturbed state can be observed at a time. Fringes are sharper than in single exposure and therefore can produce more accurate results.

Dual-hologram interferometry combines some of the advantages of the two previous methods. In this method, a finely adjustable holder is used in which two holographic plates are held. One is exposed at an original state and the other at some final state. Both are then developed together in order to eliminate emulsion differences. After processing, the plates are placed back in the holder and adjusted so as to produce the desired fringe patterns.

Real time interferometry uses single-exposure techniques and can provide a time series with only one developed hologram required for each view. By exact replacement of the developed hologram, the fringes can be made more visible by varying the beamsplitter to increase the intensity of the reference beam. By finely adjusting the hologram, the fringes can be adjusted hortizontally or vertically as a reference. Changes in temperatures, pressure, or strain will cause the fringes to deform. Positioning of a camera in-line with the object on the opposite side of the hologram plate will permit data recording. By establishing an area in which the fringes remain constant, the density field can be reduced with the aid of a computer. This technique provides a real time analysis of a changing system without the need for expensive and time consuming sensors and calibration. Using high-speed recording film, a motion picture camera can replace the standard camera for a continuous data record. This method is limited by the time it takes to reduce the acquired data.

III. EXPERIMENTAL PROCEDURE

Flexibility was the major concern in the experimental arrangement. Holography constrains the setup by requiring the distances traveled by the reference beam and the object beam to be equal. The experiment was constucted on a table mounted on inner tubes for stability. Equipment was arranged on an ellipse with mirrors located at the minor axes, the beam splitter at one major axis, and the hologram holder at the other major axis. A beam deflector was used to orient the laser with respect to the beam splitter. Spatial filters were used to clean the beam and expand it. The test section and diffuser were placed between the object mirror and the hologram holder (Figure 7 & 8).

Both the reference and scene beams should be in a single transverse mode. By fine alignment of the spatial filters, the laser beam can be focused and directed relatively free of noise with a pure transverse mode. In both the object and the reference beams an additional lens was required to expand the beam further. Originally diffuse glass was used as a diffuser screen but an improved grain pattern was required. The final diffusing screen consisted of a large piece of developed film mounted on plexiglass and secured in a rigid metal frame (Figure 4).

Choice of the hologram holder is important in live fringe holography. Accuracy requires the reconstructed virtual image and the original object to be exactly matched. As the emulsion on the hologram dries after processing, the virtual image is displaced. This problem is

solved by using an inplace-developing hologram holder which maintains the hologram in an aqueous environment. Also the hologram is secured in a removable structure which remains attached during processing of the hologram and permits exact replacement. Two micrometers are used to finely adjust the hologram after replacement.

The test section consisted of a four-inch square plexiglass box filled with distilled water. Heat transfer plates were located on the top and bottom and an air space surrounded the entire section. This air space was provided to enable a vacuum to be applied. The temperature differential did not affect this zone and the fringe lines remained constant and served as a reference for data reduction. A grid pattern was attached on the back to assist in alignment and data transfer (Figure 5). Two water circulators were connected to the heat plates. One had a reserve temperature of 25° C and the other of 45° C. Through the use of valves, either or both could supply water to the heat plates (Figure 6).

Once the system was aligned, the experimental procedure was relatively uncomplicated. Water at 25° C was circulated through both plates until equilibrium was reached in the distilled water in the box. A shutter was then placed in front of the laser beam and an Agfa-Gevaert Inc. 10E75 holographic recording plate was placed in the holder and exposed for one-half second (Figure 1).

The plate was then removed, developed, and replaced in its exact position. Fringe lines appeared and their visibility was adjusted by varying the illumination by means of a variable beam splitter. Through fine adjustment of the micrometers, the fringe pattern could be rotated to a convenient position. Water at 45° C was then allowed

to flow into the bottom heat exchanger and photographs of the changing fringe patterns were made at regular intervals.

Rigid apparatus was a major requirement. The hologram holder and the test section must be mounted on a solid base and rendered incapable of motion. If possible they should be physically attached and the base bolted to the table. Tubes carrying the heated water into the heat exchanger plates should be securely bound together and attached to the table. Vibration or motion of the test section will cause the fringes to disappear, or appear random. Also the laser, direction changer, spatial filters, and mirrors should be weighted down to make them immovable. All compressors, fans, and vibrating machinery in the building should be secured during the test. In one test a ventilation fan started up in the corner of the room and the fringe pattern was destroyed.

Data recording was accomplished by positioning a camera in a direct line with the test section at an equal distance on the far side of the hologram plate. The virtual image beam and object beam were then focused on a film plane and recorded (Figure 2). High speed recording film was used since the helium-laser was of relatively low power. Complete reduction of a three-dimensional field would require that the test section be mounted on a separate platform and rotated to allow a hologram and a set of photographs to be taken every fifteen degrees through a ninety-degree scan.

IV. THEORETICAL RESULTS

A. BASIC EQUATIONS AND VARIABLES

1. Variables

I= intensity

L= wavelength of laser

f= frequency of wave oscillation

S= speed of light

$\bar{a}$= amplitude

$\overline{V}$= electric field vector

$\bar{e}$= complex amplitude

w= phase function

d= spacing between fringes

v= resolution of hologram medium

Nt= efficiency

Te= exposure time

P= power

A= exposure area

E_o= average energy

E= energy

2. Basic Relationships

Understanding holography requires an understanding of the basic holographic and photographic equations. The important relationship in photography is that intensity reduces to the square of the amplitude of a single light wave. The energy per unit volume can be stated:

$$u = 1/2\ E\overline{V} \cdot \overline{V}$$

Taking the time average over 2T yields:

$$/u/ = 1/2\ T\ S_{-T}^{+T}\ u\ dt$$

Substituting from above:

$$/u/ = 1/2E \cdot 1/(2T)\ S_{-T}^{+T}\ \overline{V} \cdot \overline{V}\ dt = 1/2\ E/\overline{V} \cdot \overline{V}/$$

If one considers a single light beam, the intensity at a point is the time average of the energy per unit volume times the speed of light. Intensity may be defined as

$$I' = S/\ u\ / = 1/2\ SE/\overline{V} \cdot \overline{V}/$$

Normally in photography the intensity is defined as

$$I = 2/\ \overline{V} \cdot \overline{V}\ /$$

By defining the electric field vector and substituting into the above equations for a period much greater then the inverse of the frequency, the intensity for single light beams becomes:

$$\overline{V} = \bar{a}\cos(2\pi ft + w)$$

$$I = 2/2T\ S_{-T}^{+T}\ (\bar{a} \cdot \bar{a}\ /2)\ (\ 1 + \cos\ (\ 4\pi ft + 2w)\ dt$$

$$I = a^2$$

This is the basic photographic equation.

Holography records the interference of two wave fronts. Introducing the complex electric field vector leads to the solution of the basic hologram equation. This complex vector contains the temporal phase factor varying at the oscillation frequency. The complex electric field vector is

$$\bar{V} = \bar{a} \exp(iw) \exp(2\pi i f t)$$

where the complex amplitude vector is

$$\bar{e} = \bar{a} \exp(iw) .$$

Again determining the intensity, one has

$$I = \bar{a} \cdot \bar{a} = \bar{e} \cdot \bar{e}^{*}$$

which upon substitution yields

$$I = \bar{a}_1 \cdot \bar{a}_1 + \bar{a}_2 \cdot \bar{a}_2 + \bar{a}_1 \cdot \bar{a}_2 (\mathrm{ExP}(i(w_2 - w_1)) + \mathrm{ExP}(-i(w_2 - w_1)))$$

$$I = I_1 + I_2 + 2\,\bar{a}_1 \cdot \bar{a}_2 \cos(w_2 - w_1).$$

This final equation is the basic hologram equation which relates intensity, amplitude and phase for two interfering waves.

Interference fringe paterns are produced on the hologram slide by interference of the two wavefronts. Each wavefront intensity remains the same, but the total intensity is a maximum when the cosine of the phase function difference is equal to one, and a minimum when it equals zero. The maximum contour surface is

$$w_2 - w_1 = 2\pi N , \; N = 0, 1, 2, 3, 4, \cdots\cdots\cdots .$$

B. HOLOGRAM RECORDING

Agfa-Gevaert 10E75 recording plates were used to record these holograms. These plates consist of glass slides coated with an emulsion 6μm thick. This emulsion is extremely fine grains of silver halide compounds dispersed in a gelatin and a sensitizing agent. The interference fringes are recorded in this absorption material as a spatial variation of the light which is incident on it.

1. Characteristics of 10E70 Plates

Required energy density	3-6μJ/cn^2
Maximum diffraction efficiency	4%
Resolution	2800 lines/mm
Spectrum	5800-6700Å (approx.)
Optimum wavelength	6400Å (approx.)
Optimum exposure	2.5μJ/cn^2

2. Variables Used

Nt= net power transfer efficiency from laser to recording material

P = output power of laser

Te= exposure time

Eo= average exposure value

3. Calculations

The resolution required to record the phase information in a hologram must be less than the resolution of the plate used. The 10E75 recording plates have a resolution of 2800 lines/mm. Using a wavelength of .633 μm for the He- Ne laser and an angle of 31°, the

required resolution can be found if a volume hologram is assumed.

$$2d \sin \Theta = L$$

$\Theta = 31^{o}$

$d = 614.5\ \mu m$

$v = 1627.3$ lines/mm

Required resolution = 1627.3 lines/mm

Resolution of the plates = 2800 lines/mm

With an exposure of one-half of a second, the energy reaching the holographic plate can be estimated.

$Nt = .04$

$Te = 0.5$ seconds

$P = 15$ milliwats

$A = 100$ square centimeters

$$E_o = \frac{Nt \times Te \times P}{A} = 3 \mu J/cm^2$$

4. Processing

Following exposure, the plate is processed for eight minutes in Kodak D-19 developer with constant agitation. The hologram plate is then put in an acetic acid stop bath for thirty seconds and a fixer for five minutes. Real-time interferometry requires exact positioning of the reconstructed virtual image on the original object. For this reason shrinkage of the emulsion should be avoided. An emulsion shrinkage of the wavelength causes a 180^{o} phase reversal of the reconstructed wavefront. Some shrinkage effects can be avoided by keeping all baths and rinses at the same temperature. Another shrinkage of up to 15% occurs due to the removal of unexposed silver halide grains from the gelatin during fixing. Since the hologram

is to be used immediately, the full fixing time is not required although some fixing is needed to clear up the cloudiness. Another method is to fully process the plate but soak it after fixing in triethanolamine $(CH_2OHCH_2)_3N$. This will swell the emulsion back to its original thickness. Drying will also shrink the emulsion but replacement of the hologram plate into a wet inplace hologram holder makes drying unnecessary.

5. Recording of the Fringes

The fifteen milliwatt helium-neon laser does not have enough power to produce highly visible fringe lines. Fringe lines must be viewed in the dark with the only light coming from the laser. The real image from the virtual image rays did not contain enough energy for it to be focused on ground glass. The fringe lines also appear to be located on a plane at infinity. This makes the fringe lines remain stationary as the observed angle changes and the box appears to move behind the fringe lines. For these reasons a high quality single lens reflex camera was used. This camera permitted focusing on the fringe lines and an f-stop of 16 allowed a large field of view and a small enough opening to eliminate all but direct rays.

The best film to use in real-time interferometry with the He-Ne laser is Kodak 2485 High-speed Recording Film with Estar-AH base. This film has an ASA of 8000 and is sensitive at the required 6328 Å wavelength. Interference fringes must be enhanced in the recording process due to their poor contract. This requires a high contrast range film such as the Kodak 2485. Unfortunately this film is not available in the limited quantities needed. Kodak 2475

Recording Film with an Estar-AH Base is readily available in a 35 mm magazine or 16 mm movie film configuration and was used instead of the preferred film. The 2475 film has an ASA rating of 1000 to 6500 but does not have the high contrast qualities of the 2485 film. Either of these films can be used with any red-emitting laser and special processing can increase the ASA rating.

C. HEAT TRANSFER ANALYSIS

Significant work has been done to analyze external flow as in heat transfer into a stationary fluid due to a heated plate. Little has been done in the study of internal heat flow in an enclosure. Heat convection in enclosures is important in insulation but analysis has been hindered by the complexity of the heat transfer problem. Studies have taken place on rectangular sections with varying height-to-width ratios and on pipe sections. Heating takes place from the sides or from the bottom. Simplified solutions require an infinitely long test section and a two-dimensional analysis through a horizontal axis.

A. F. Pillow in 1952 demonstrated heat transfer between two infinitely long horizontal surfaces. The bottom surface was maintained at a higher temperature than the top and a thermally unstable condition was created. A cellular motion was set up after a critical Rayleigh number was reached for a given large Grashof number and a unit Prandtl number. As the Grashof number increases to infinity, the viscous and thermal diffusion terms can be neglected. This simplified solution yields an isothermal interior with uniform vorticity. Heat transfer was assumed to follow a 5/4th power law of the temperature

differences. This relationship was shown by W. Mull and H. Reiker in 1930.

A general nondimensional analysis of the problem by S. Eskinazi is helpful in understanding the non-dimensional parameters involved. Ten independent quantities are involved.

U= Characteristic volocity	Cp= Specific heat
l = Characteristic length	K = Thermal Conductivity
p = Density of fluid	h = Film coefficient
μ = Visocosity of fluid	Θ = Temperature differnece
g = Gravitational acceleration	B = Volume-temperature expansion coefficient

Basic Relationship

$$f(U,\ l,\ p,\ \mu,\ g,\ Cp,\ K,\ h,\ \Theta,\ B) = O$$

Expansion in terms of a power series, substitution of powers, units and values, and combining factors with similar powers yields an equation.

$$\left(\left(\frac{pUl}{u}\right)^a \left(\frac{l^3 p^2 g}{u}\right)^e \left(\frac{hl}{K}\right)^m \left(\frac{Cpu}{K}\right)^i \quad (\Theta B)^p\right) = M^o L^o T^o H^o \Theta^o$$

$$\phi\left(\frac{pUl}{u}, \frac{l^3 p^2 g}{u^2}, \frac{hl}{K}, \frac{Cpu}{K}, B\Theta\right) = O$$

Futher analysis shows that the power "e" and the power "p" must be equal since the specific buoyant force is $(p_2 - p_1)g$ and is equal to the change in density with temperature term $p_1 B\Theta$. If this simplification is applied one has:

$$\phi\left(\frac{pUl}{\mu}, \frac{l^3 p^2 g}{\mu^2}, \frac{hl}{K}, \frac{Cp\mu}{K}\right) = O$$

ϕ (Reynolds#, Grashof#, Nusselt#, Prandtl#) = O

For the specific problem of enclosures, the Grashof and Prandtl numbers are the most important. The product of these non-dimensional coefficients is equal to a coefficient called the Rayleigh Number.

Heat flow for a rectangular cross-section showed convection to be insignificant compared to conduction at low Rayleigh numbers. Convection was restricted to the upper and lower ends of the section. As the Rayleigh number approached the threshold of a boundary layer analysis, the convection tended to propagate out from the corners.

W. Martini and S. Churchill in 1960 considered the problem of natural convection of air within a horizontal cylinder with both sides heated to different temperatures. The Rayleigh number was varied from 2x10E+6 to 8x10E+6. This study showed that most of the flow took place adjacent to the walls and the interior region remained relatively stagnant. The temperature distribution in the interior consisted of a stratified fluid with horizontal isotherms which increased in temperature vertically. Eckert and Carlson in 1961 reduced the temperature field for a low Rayleigh number using a Mach-Zehnder interferometer. They showed a heat transfer to take place by conduction in the central region with convection restricted to the corners prior to boundary layer region formation. Above a critical Rayleigh number and below a critical height-to-width ratio, a boundary layer region developed with results similar to Martini and Churchill.

S. Weinbaum in 1964 used a pipe to show the difference between side heating and bottom heating. The interior region was isothermal

with constant vorticity for both. With bottom heating, the interior rotated essentially as a solid body. The core streamlines were closed, which implies a rotating isothermal core. Side heating produced a stagnant core which is thermally stratified with relatively slow flow. Bottom heating can also create a double or single cell with each formation being equally probable.

These studies involved two-dimensional simplifications. Application of them to a box can cause many a problem. Solid boundaries exert a stabilizing influence and therefore motion is first expected along the largest dimension. A square box has no largest side and also has three-dimensional effects for the boundary layers of the ends. These end effects preclude the formation of purely planar cells and make a two-dimensional approach unsuitable. Many instabilities are also present which further complicated the problem. A nice analytic solution is not possible, but holographic interferometry can supply experimental information on the three-dimensional temperature field with the help of a computer for data reduction.

V. ALTERNATE METHODS

In the formation of an experimental procedure many different techniques were used. Various films were used to record the reconstructed images. Different methods of processing and recording the holograms were also tried.

Bleaching of the developed hologram increases the diffraction efficiency significantly. The bleach oxidizes the silver deposited in the emulsion and forms silver ions. These ions react with

negative ions in the bleaching solution and produce silver salts. This salt has a different refraction index from the gelatin on the plate. Bleaching increases the possible diffraction efficiency from a value of around 4% to almost 70% and is effective for high resolution phase holograms. One disadvantage is the increase in scatter which increases the noise level over the unbleached hologram.

An experiment was performed using Kodak Chromium Intensifier. The hologram plate was slightly overexposed and then developed normally. After rinsing, the plate was placed in the bleach until the black emulsion turned yellow. The bleached plate was then rinsed and emersed in a sodium bisulphite bath to remove the excess dichromate. After the plate turned white it was removed and rinsed. Reilluminating the bleached hologram produced a much brighter image. By fitting the plate with a cover slide over a xylene coating, the noise was significantly reduced. The noise was caused by the non-uniform surface of the emulsion the the xylene served as an index matcher.

Although bleaching was highly effective in producing a brighter image, it was not useful in real time interferometry. The resulting shrinkage and alteration of the emulsion displaced the reconstructed virtual image above and behind the original object. This displacement made the formation of fringe lines impossible. One possible use of bleaching is in dual-hologram interferometry where the holograms can be processed and bleached together. By the equal treatment, the image should be equally displaced and the fringes should be visible with a much higher diffraction efficiency.

Many different physical arrangements were used before the elliptical pattern was chosen (Figure 4). Collimating the light

directly as it exits the laser is desirable, but the need for a variable beam splitter made this impossible. Without the variable beam splitter the relative intensities could not be adjusted to give maximum fringe visibility after reillumination. The placement of the spatial filters is arbitrary and can be adjusted to give the proper expansion. By positioning the mirrors on the axis of the ellipse, either can be moved independently without changing the optical path lenghts significantly. The test section can also be positioned anywhere between the mirror and hologram holder. This allows for maximum versatility and reliability.

For a complete experimental solution to the heat transfer problem, a series of views would be required. This could be done by mounting the test section on a turntable capable of rotation and translation. One hologram and a complete set of photographs would be required from each position. The heating water temperature would be maintained at a constant temperature for each run with the 25° water circulating in both plates at the start of each test. A timing schedule would be initiated when the 45° C water is sent into the bottom heat exchanger plate and pictures would be taken at specific intervals. This procedure would allow good correlation between the fringe patterns obtained at each angle and position. The experiment that was performed only considered one angle and one position.

An interesting application is the use of a motion picture camera as the recording medium. The motion picture camera would continuously monitor the changing fringe pattern. Individual frames could be selected from the developed film and measurements taken. Two

advantages of this are an accurate time reference and the capability of observing the fringe changes after the experiment is completed. In non-destructive testing, it would constantly monitor the fringe pattern from one view and allow a record to be kept. For these reasons a motion picture film was included in the experiment.

VI. CONCLUSIONS

Although difficulties were encountered, real time holographic interferometry using a similar setup to the one described in this thesis is feasible in solving the problem of heat flow in enclosures. Constant fringe lines were visible across the entire enclosure. The fringes remained constant outside the enclosure and changed only inside the box. The constant pattern served as a reference.

Final tests yielded clear fringe patterns with an initial system of parallel lines separated by about three millimeters. By recording the holograms at one temperature for both heat plates and then reilluminating the hologram and test section with the plates at a slightly higher temperature, the fringe lines become curved upwards slightly. As the bottom plate has hot water circulated through it at a 20^{o} C differential, the fringe pattern inside the box starts to change. Perturbations start to form at similar locations along the fringe lines. These grow vertically and vertical ripples through them are detectable. As a steady state is reached, the fringe lines deform and become symmetric about the corners. Further study is required to determine whether the center can be considered a rotating mass with convection limited to the corners. As the heating progresses,

the visibility of the fringes diminishes and eventually can disappear. Review of a motion picture reconstruction is desirable since the changes occur rapidly.

Reconstruction using a low powered helium-neon laser is extremely difficult. Small shutter openings are required to achieve a reasonable depth of field at the close distances required. Also a reasonable shutter speed is required due to the motion of the fringes. Recording was done with a Yashica TL-electro X single-lens reflex camera. With 2475 recording film, pictures of the virtual image are not possible at any speed greater than .25 seconds. Images start to appear at one-thirtieth of a second. Special development was not available, but pushing the ASA to higher values would increase the grain size to unacceptable values. For these reasons the shutter should be opened all the way and the camera focused on the fringes. Photographs should be taken at a speed of .03 to .1 seconds. Kodak 2485 High Speed Recording Film is of limited availibility but is highly desirable. Using standard Kodak D-19 developer an ASA of 6500 is realized and special processing will give an ASA of 8000. This compares with an ASA of 1000 for 2475 film with processing in Kodak D-19. Special processing of the 2475 movie film was possible but had to be limited in order to keep grain size small.

Highly sucessful results were obtained with the motion picture camera. Single frames were of poor quality and contrast but the showing of many frames with a motion picture camera greatly improved the visibility of the fringes. Time average photos were taken of the projected image on a screen. The developed movie film showed a round circle in the center which was the laser beam. On either

side dark areas show up from reflections off the side of the test box. In the middle area vertical fringe lines are supperimposed over these images (Figure 9). As the heat is first applied to the bottom of the box, the fringe lines remain steady and vertical with a slight lean to the left (Figure 10A & 10B). The bottom of the box then breaks out into a change of phase which is visible as dark spots on each fringe line at almost the same position. This appears as a horizontal black line (Figure 11). Very rapidly these phase shifts travel vertically along the fringe lines as the convection takes place vertically. The base of the fringe lines now appear as wisps of smoke (Figure 12). Finally the entire section is affected by the phase changes brought on by convection, and the vertical fringes wave and have repeated series of horizontal black wavy lines traveling up the fringes (Figures 13, 14, & 15).

From the final results, a need for high speed and high resolution film is shown. Use of a helium-neon laser of fifteen milliwatt power is also very limiting, a fifty milliwatt helium-neon laser or a laser of even more power is desirable. Lasers with powers on the order of one-watt would possibly permit television camera recording of the changing virtual image fringe pattern. This would be highly beneficial in non-destructive testing and would provide more information than the double-exposure holographic techniques. Heat flow is a complex problem and if information about the end states is not sufficient, real-time holographic interferometry offers an opportunity to observe the changes between these end points.

APPENDIX A

Figure 1 Recording the hologram

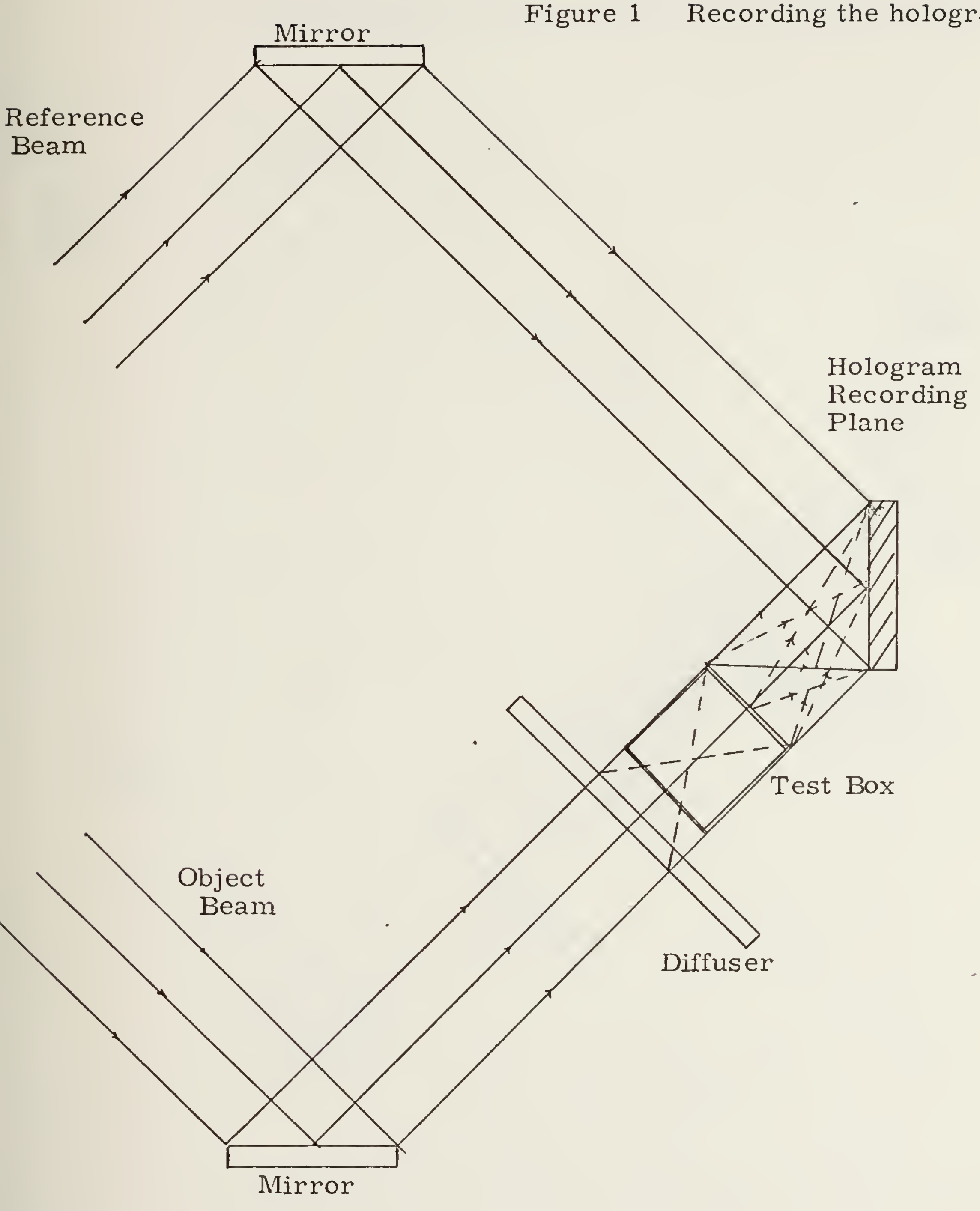


Figure 2

Reconstruction and recording of the interference patterns

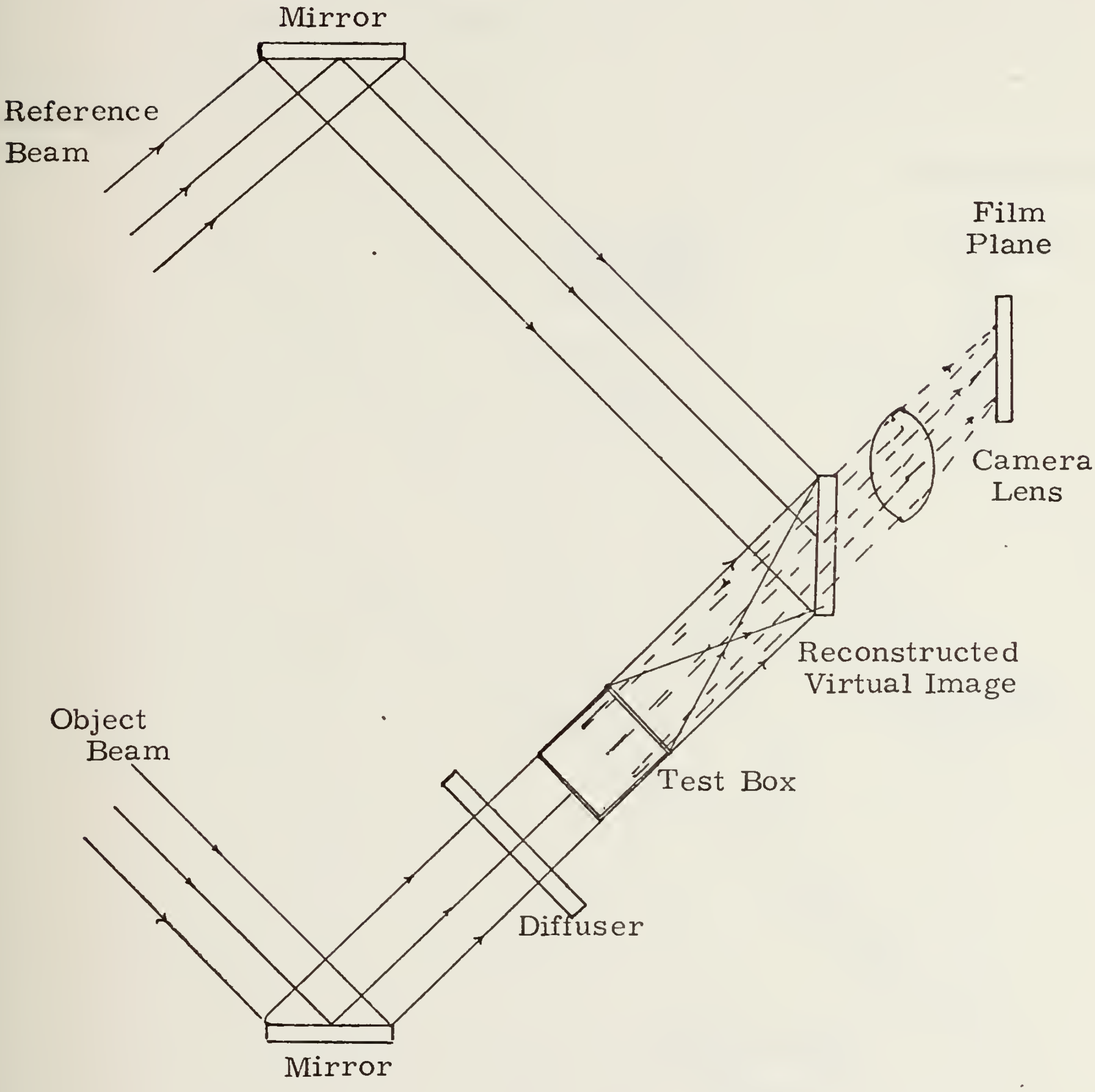


Figure 3

Real image reconstruction

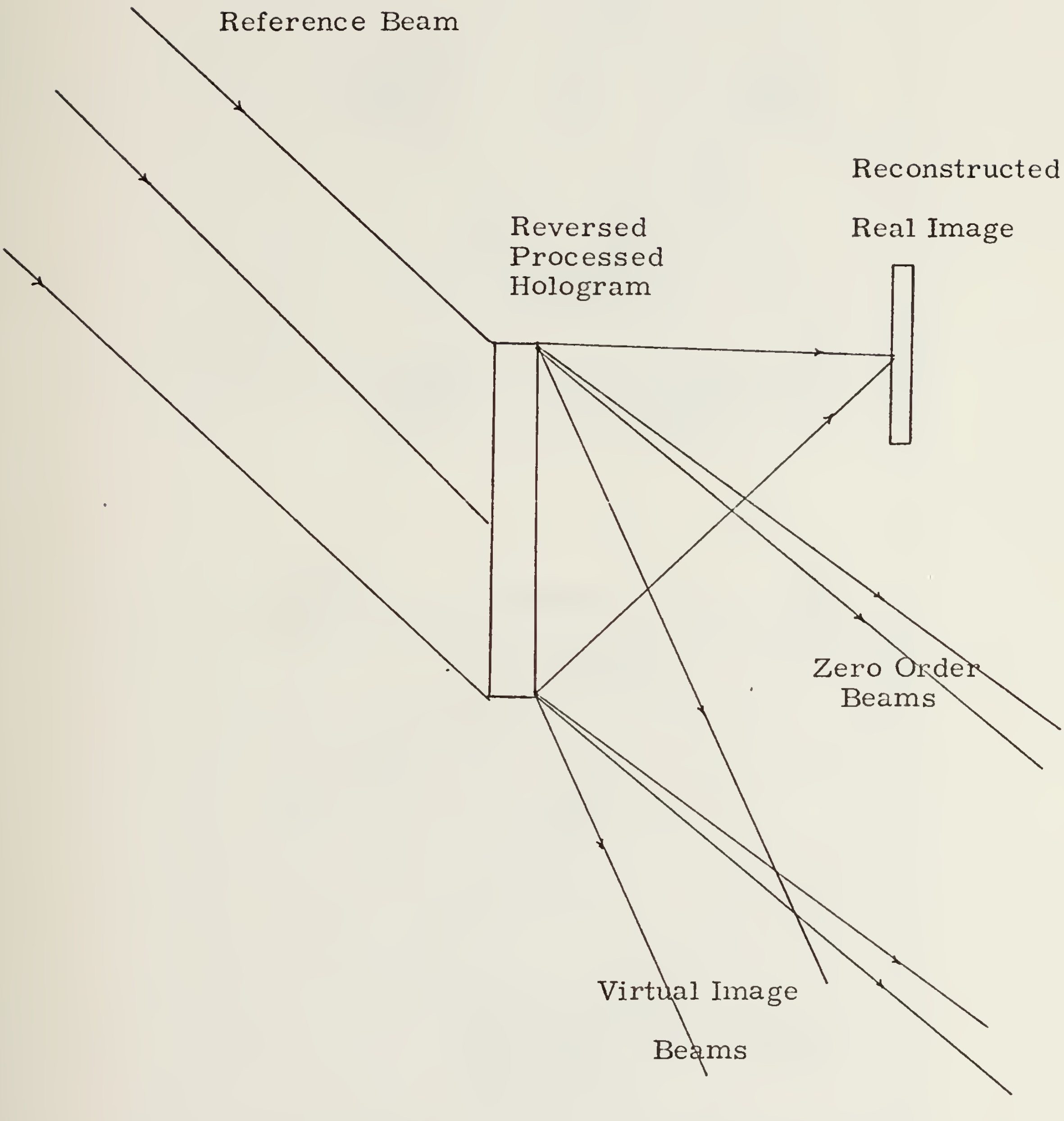
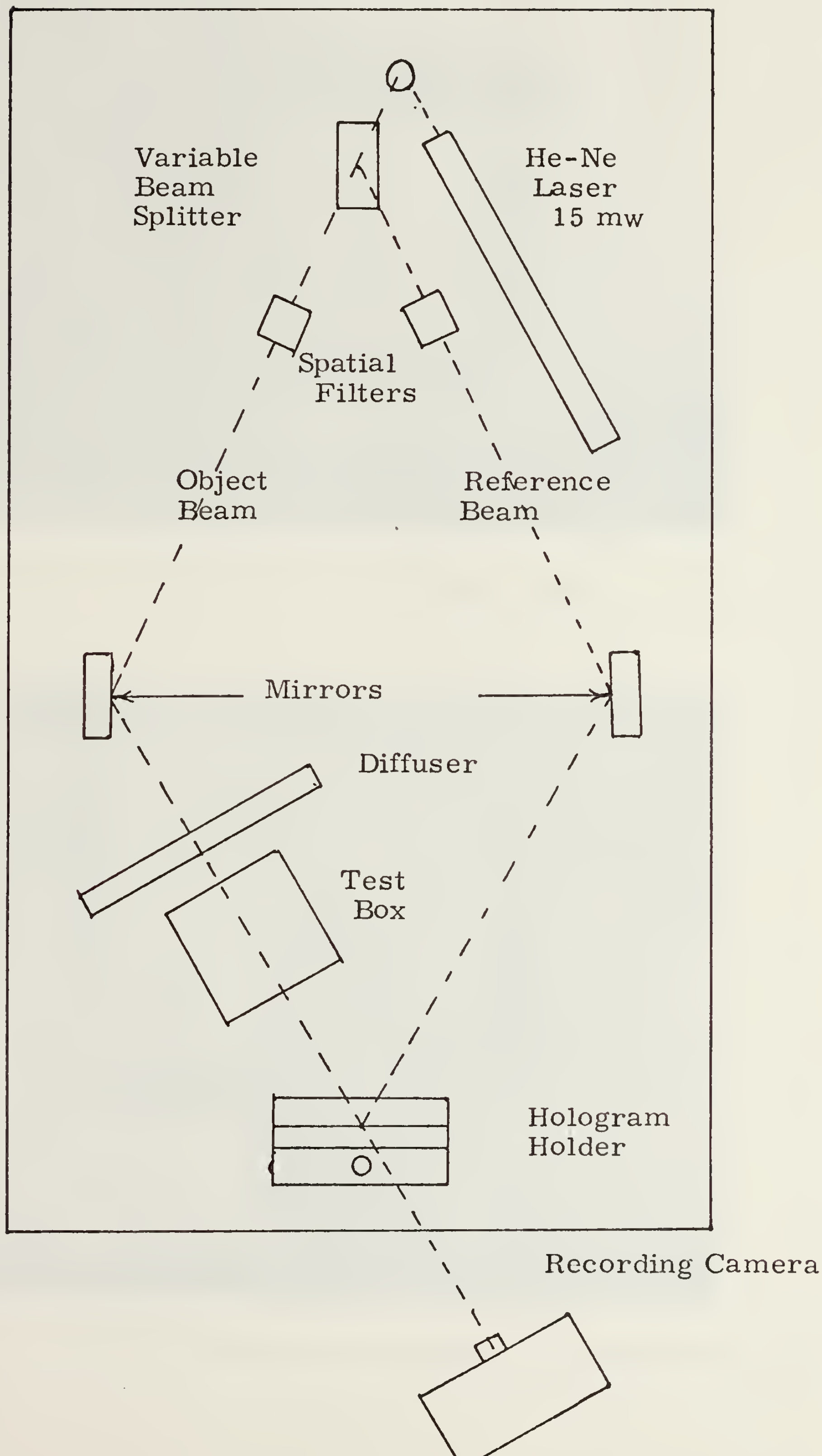


Figure 4

Table arrangement



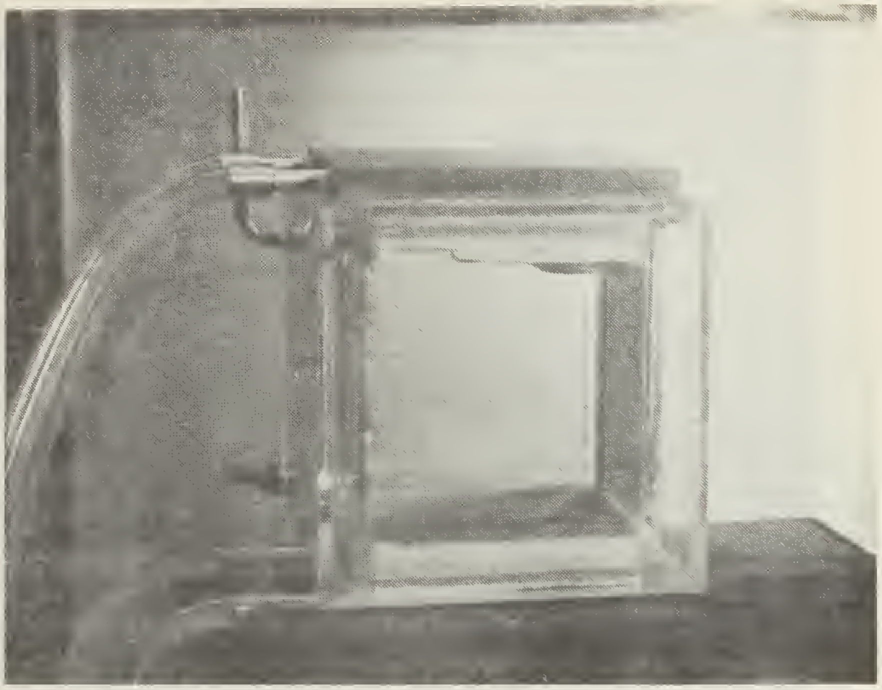


Figure 5 Test box with heat exchanger plates

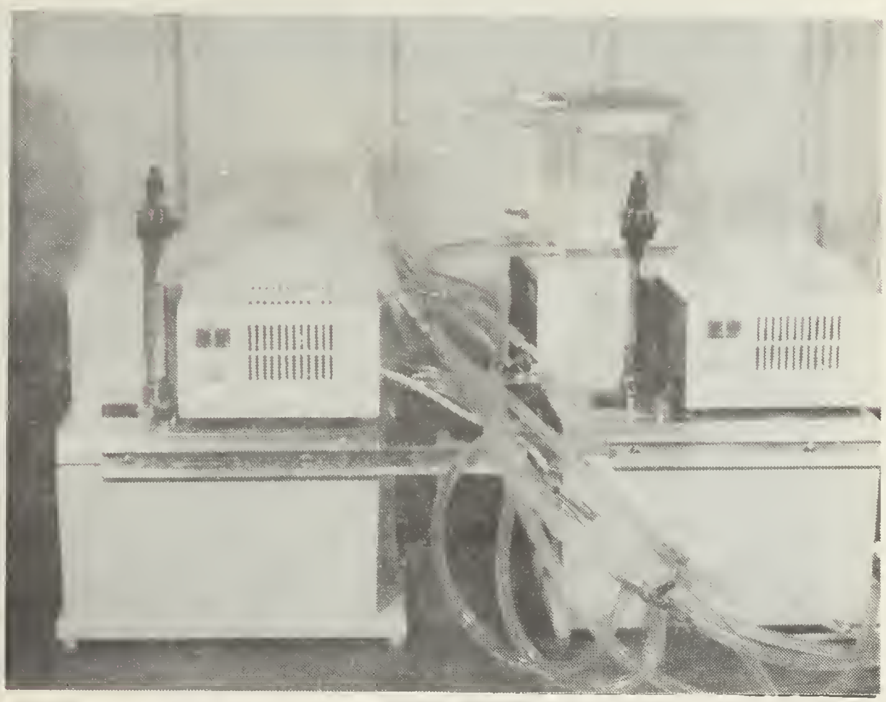


Figure 6 Water heaters and circulaters connected to test box

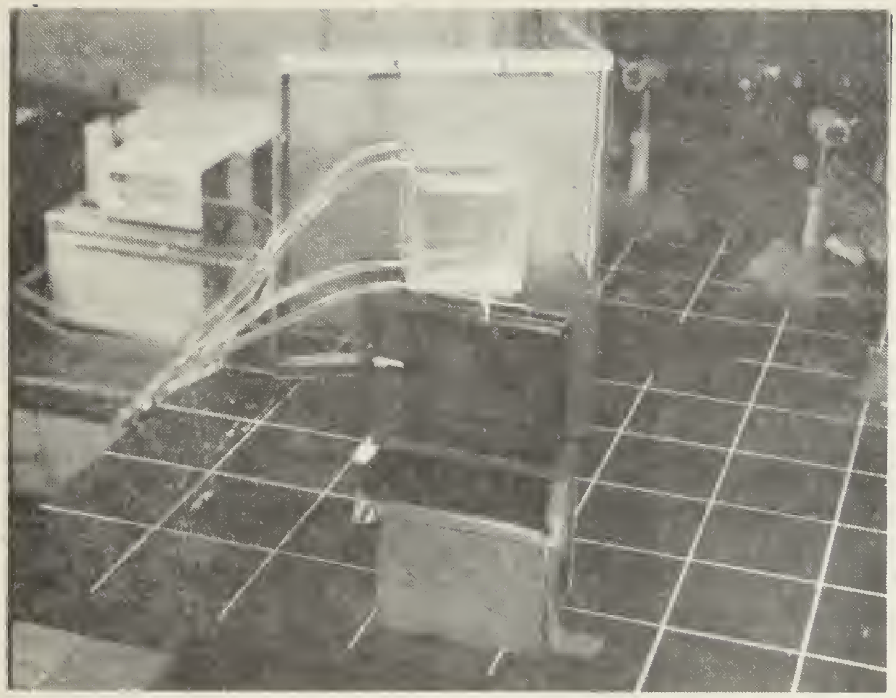


Figure 7 Experimental apparatus viewed from recording plane

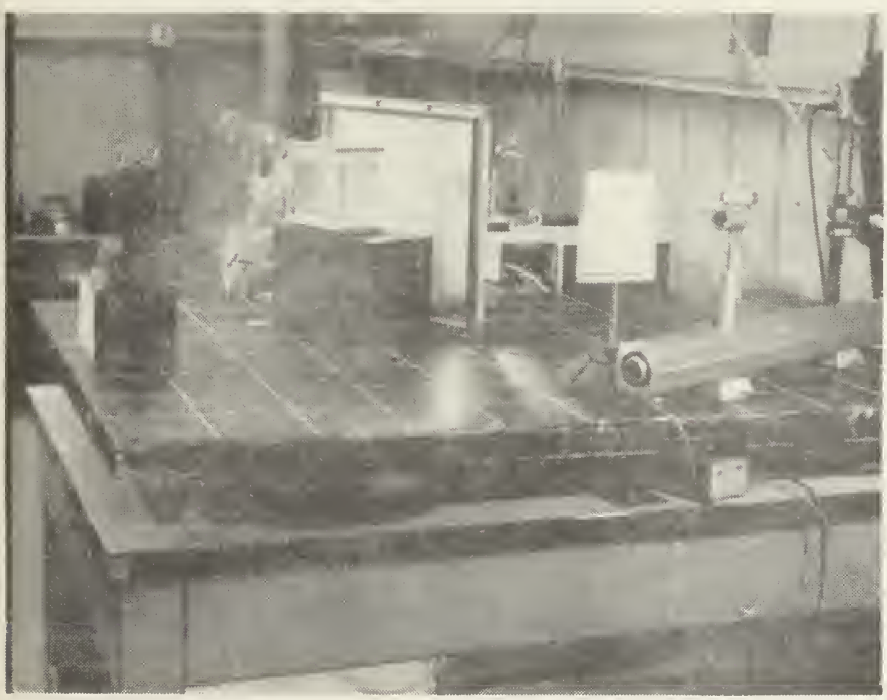


Figure 8 Arrangement of apparatus on test table

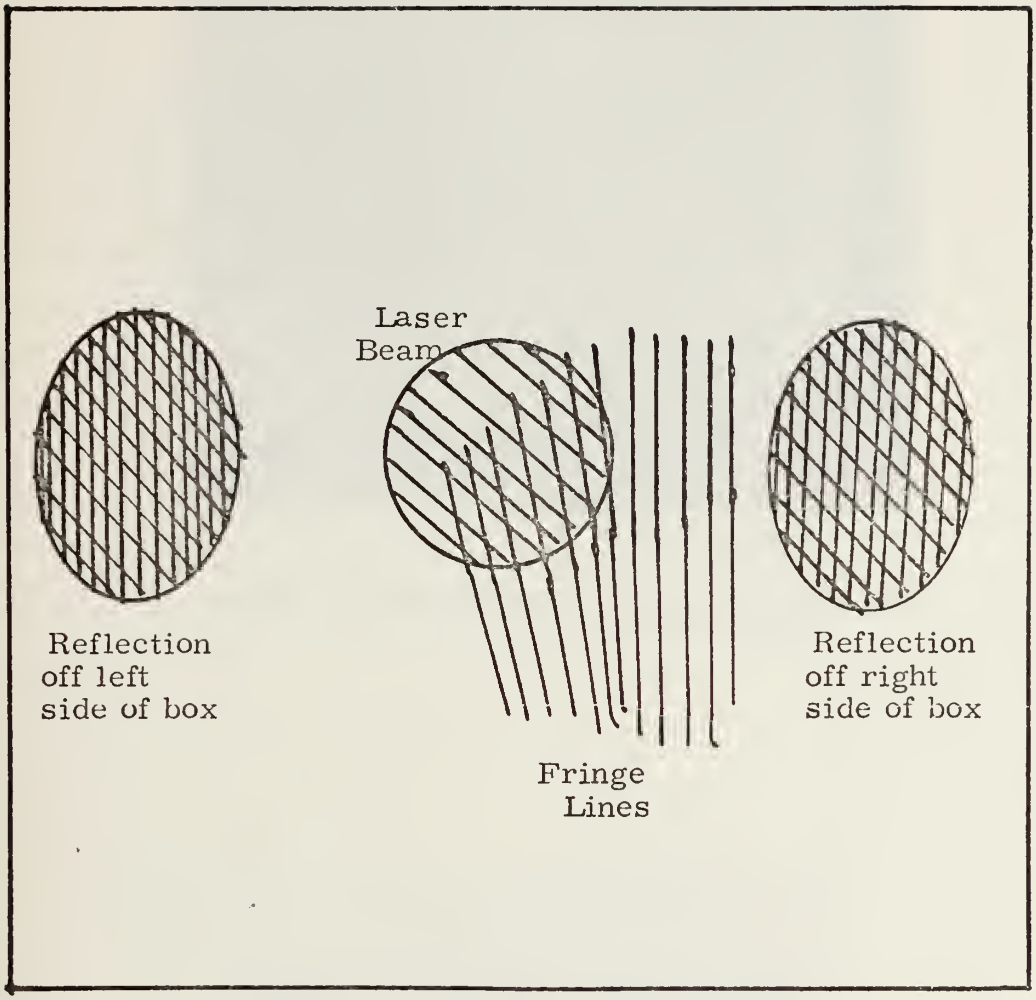


Figure 9 Movie Camera Recording

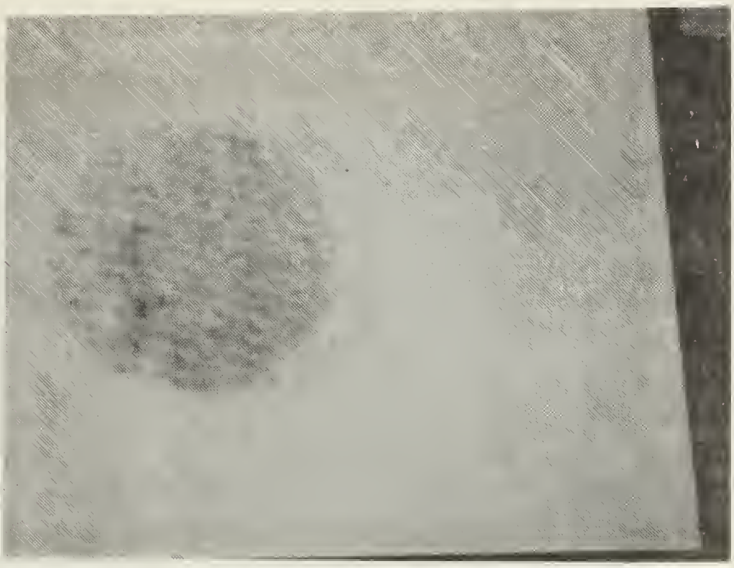
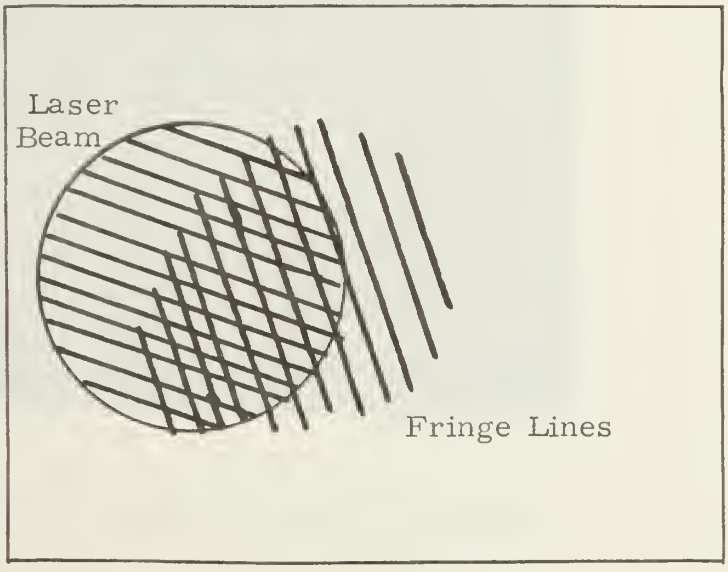


Figure 10A Steady State Fringe Photograph

Figure 10B Drawing of Photograph



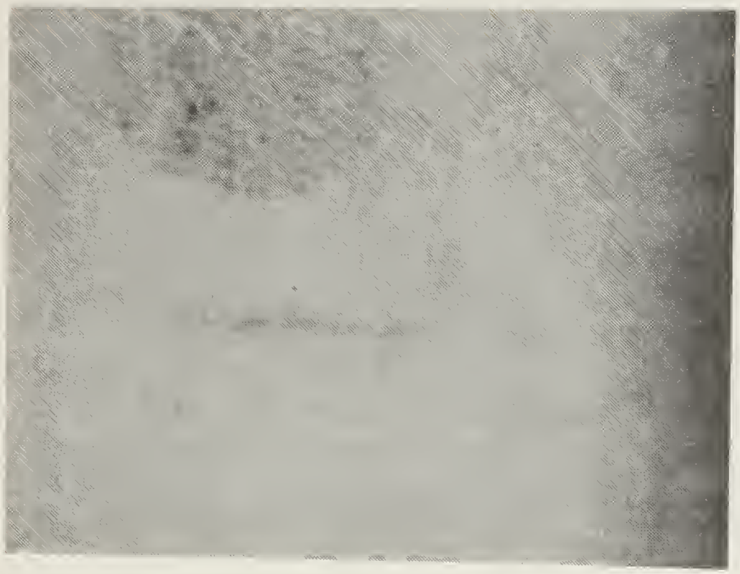


Figure 11 Start of Heat Flow

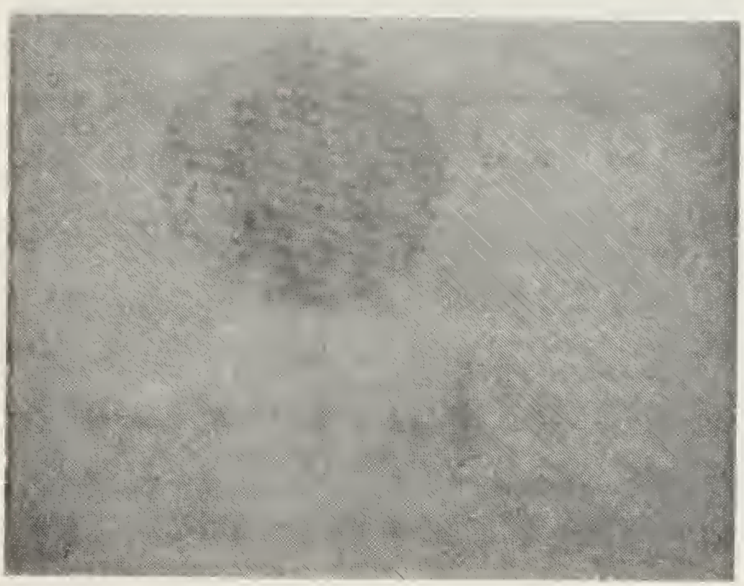


Figure 12 Phase Shift Move Vertically

Figure 13 Fringe Pattern Established

Figure 14 Continued Phase Shifts

Figure 15 Circular Fringe Pattern Starting in Center With Vertical Fringe Pattern to the Right

LIST OF REFERENCES

Caulfield, H. J. and Sun Lu, The Applications of Holography, Wiley-Interscience, 1970

Collier, J. C., Burckhardt, C. B., and Lin, L. H., Optical Holography, Academic Press, 1971

Collins, D. J., Measurements of Velocities in Single and Two-Phase Flows, von Karman Institute for Fluid Dynamics Lecture Series 54, February 19-23, 1973.

Eskinazi, S., Principles of Fluid Mechanics, 2d ed., p. 480-482, Allyn and Bacon, Inc., 1968

Gebhart, B., "Natural Covection Flows and Stability," Advances in Heat Transfer, v. 9, p. 273-348, Academic Press, 1973.

Hecht, N. L., and others, "Quantitative Theory for Predicting Fringe Pattern Formation in Holographic Interferometry," Applied Optics, v. 12, No. 11, November 1973.

National Aeronautics and Space Administration Technical Report R-409, The Application of Holography as a Real-Time Three-Dimensional Motion Picture Camera, by Robert L. Kurtz, September 1973.

Ostrach, S., "Natural Convection in Enclosures," Advances in Heat Transfer, v. 8, p. 161-226, Academic Press, 1972.

Radley, R. J. and Havener, A. G., "Dual-Hologram Interferometry: A New Technique for Wind-Tunnel Testing," Astronautics & Aeronautics, v. 11, No. 12, p. 27-29, December 1973.

Saito, H., Yamaguchi, I., and Nakajima, T., "Application of Holographic Interferometry to Mechanical Experiments," Applications of Holography, p. 105-126, Plenum Press, 1971.

Smith, H. M., Principles of Holography, Wiley-Interscience, 1969.

Smith, P. R., Peters, T. M., and Bates, R. H. T., "Image Reconstruction from Finite Numbers of Projections," J. Phys. A: Math., Nuel., Gen., v. 6, p. 361-382, 1973

Stein, K. J., "Holographic Map Display Developed," Aviation Week & Space Technology, p. 50-51, April 22, 1974.

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